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Request for grant of a patent

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1. Your reference — 610GB

14NOV03 E852091-1 002851
P01/7700 0.00-0326532.9

2. Patent application number *(The Patent Office will fill in this part)* — 0326532.9

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

Renishaw plc
New Mills
Wotton-under-Edge
Gloucestershire, GL12 8JR

Patents ADP number *(if you know it)* — 2691002

If the applicant is a corporate body, give the country/state of its incorporation — United Kingdom

4. Title of the invention — Method Of Error Compensation

5. Name of your agent *(if you have one)* — E C Leland et al

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Renishaw plc, Patent Department
New Mills
Wotton-under-Edge
Gloucestershire
GL12 8JR

Patents ADP number *(if you know it)* — 2691003

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
–	–	–

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*
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8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
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Yes

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Continuation sheets of this form	0
Description	10
Claim *(s)*	0
Abstract	0
Drawing *(s)*	4 + k

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Priority documents	0
Translations of priority documents	0
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	0
Request for preliminary examination and search *(Patents Form 9/77)*	0
Request for substantive examination *(Patents Form 10/77)*	0
Any other documents *(please specify)*	0

11. I/We request the grant of a patent on the basis of this application.

Signature [signature] Date 12.11.03

AGENT FOR THE APPLICANT

12. Name and daytime telephone number of person to contact in the United Kingdom: A Iles 01453 524524

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METHOD OF ERROR COMPENSATION

The present invention relates to a method of compensating for measurement errors of an articulating probe head which may be mounted on the movable arm of a coordinate positioning apparatus such as a coordinate measuring machine (CMM), machine tool, manual coordinate measuring arms and inspection robots.

It is common practice after workpieces have been produced to inspect them on a coordinate positioning apparatus, such as a coordinate measuring machine (CMM) having a movable arm onto which a probe is mounted which can be driven in three orthogonal directions X,Y,Z within a working volume of the machine.

Accelerations of the probe cause dynamic deflections of the coordinate measuring machine which in turn cause measurement errors. These measurement errors may be reduced by taking measurements at low accelerations. However as productivity demands increase the CMM has a higher throughput and increased inspection speeds are required. As the inspection speed increases, the probe experiences higher accelerations during the measurements and larger dynamic structural deflections of the CMM result. This causes inaccurate reporting of the X,Y,Z geometric position of the probe.

Our earlier patent US 4,333,238 discloses a method of correcting for deflection of the coordinate measuring machine caused by the probe acceleration by determining the dynamic deflection of the structure (CMM) at the instant of the measurement signal by using a sensing parameter on the structure which is effected by the

change of speed of the probe, for example an accelerometer. The output of the measuring means may therefore be adjusted to take account of this machine deflection.

US Patent No. 4,991,304 discloses another method of correcting for dynamic deflections in which a succession of nominally identical workpieces are measured using a probe on a coordinate measuring machine. A first workpiece is probed a first time at a slow speed and a second time at a fast speed. A series of error values are calculated from the differences between the fast and slow measurements. The subsequent fast measurements on succeeding workpieces are corrected by making use of these error values.

Both these prior art methods allow workpieces to be measured at a faster speed but have an upper limit above which they become unsatisfactory. This may be due to the CMM becoming inconsistent and/or unstable at high accelerations or the machine being unable to achieve the acceleration demanded.

The limitations described above can be overcome by using a high bandwidth apparatus which is mounted on the coordinate measuring machine.

Such a high bandwidth apparatus is disclosed in US Patent No. 5,189,806 which describes an articulating probe head capable of orientating a probe with two degrees of freedom to enable the probe to be used in an operation for scanning the surface of workpieces.

In general such a probe head includes a rotary drive

mechanism having a relatively fixed supporting structure and a rotary member which is rotatable relative to the supporting structure about an axis of the structure. Rotation of the rotary member is powered by a motor which, in the case of an electric motor for example includes a stator operably connected to the supporting structure and a rotor operably connected to the rotary member. Torque generated by the motor and applied to the rotary member also causes an equal and opposite reaction torque to be applied to the stator and thus to the supporting structure.

This reaction torque can cause rotation on the movable arm of the coordinate positioning machine on which the probe head is mounted leading to errors in the measurements made by the machine.

The high bandwidth apparatus such as the articulating probe head has the advantage that it can perform individual feature measurement at high speed and thus reduces acceleration demands on the coordinate measuring machine. However the apparatus has inertia and on acceleration at high speed a force or moment has to be reacted against to avoid a measurement error.

International Patent Application No. WO01/57473 discloses an articulating probe head in which at least one of the motors is inertia balanced by mounting the stator of the motor on bearings to allow it to rotate in opposition to rotation of the rotor. Control of the speed of the spinning stator is achieved by connecting it to the winding assembly of an additional back to earth motor. This method of inertia balancing the articulating probe head has the disadvantage that it

adds mass, complication and cost to the probe head.

The present invention provides a method of error compensation for measurements taken using an articulated probe head having a surface detecting device, said articulated probe head being mounted on an arm of a coordinate positioning apparatus wherein the coordinate positioning apparatus allows the articulated probe head to be positioned within the working volume of the apparatus, and wherein the surface detecting device may be rotated about at least one axis of the articulated probe head about a centre of rotation, the method comprising the steps of:

(a) determining the torque applied to the arm of the coordinate positioning apparatus at any particular instant;

(b) using the torque to determine angular deflection of the arm;

(c) determining the offset of the tip of the surface sensing device from the centre of rotation;

(d) using the angular deflection of the arm and the offset of the tip of the surface sensing device to calculate the measurement error; and

(e) correcting the measurement error.

This method therefore enables the measuring error due to high speed to be mathematically compensated for in a non-inertia balanced system.

The surface detecting device may be a contact probe which comprises a deflectable stylus with a workpiece contacting tip. For example the contact probe may

comprise a scanning probe or touch trigger probe.

Alternatively the surface detecting device may comprise a non-contact probe such as an optical, capacitance or inductance probe.

The torque may be measured or determined from a look-up table.

For a contact probe the measurement error = $(L\cos\varphi)\delta\theta$ where L is the distance between the tip of the surface sensing device and the centre of rotation, φ is the angle between the surface sensing device and an axis normal to the axis of the machine arm and $\delta\theta$ is the angular deflection of the machine arm.

Preferred embodiments of the invention will now be described by way of example with reference to the accompanying drawings wherein:

Fig 1 is a perspective view of a coordinate measuring machine;

Fig 2 is a cross-section of an articulated probe head;

Fig 3 is a perspective view of an articulated probe head mounted on the arm of a coordinate measuring machine; and

Fig 4 is a graph illustrating the relationship between torque T and Z column angular deflection $\delta\theta$.

Fig 1 illustrates an articulated scanning head mounted on a coordinate measuring machine (CMM). The articulated probe head 10 is mounted to the bottom end of a vertically extending elongate member or Z column 12 of the CMM 8. The Z column 12 is supported for

movement in the Z direction by bearings e.g. air bearings 14, which are integral with a carriage 16 which in turn is supported for movement in the X direction by a beam 18. The beam 18 is supported for movement in the Y direction by a track 20 mounted on a table 22. The articulated probe head 10 may therefore be positioned anywhere in X,Y and Z of the machine's working volume.

As illustrated in Fig 2 the articulated scanning head 10 comprises a fixed part formed by a base or housing 30 supporting a movable part in the form of a shaft 32 rotatable by a motor M1 relative to the housing 30 about an axis A1. The shaft is secured to a further housing 34 which in turn supports a shaft 36 rotatable by a motor M2 relative to the housing 34 about an axis A2 perpendicular to the axis A1.

A probe 38 with a stylus 39 having a workpiece contacting tip 40 is mounted onto the articulated scanning head 10. The arrangement is such that the motors M1,M2 of the head can position the workpiece contacting tip 40 angularly about the axes A1 or A2 and the motors of the CMM (not shown) can position the articulated probe head linearly anywhere within the three-dimensional coordinate framework of the CMM to bring the stylus tip into a predetermined relationship with the surface being scanned.

Linear position transducers (not shown) are provided on the CMM for measuring linear displacement of the articulated probe head and angular position transducers T1 and T2 are provided in the articulated probe head 10 for measuring angular displacement of the stylus 39

about the respective axes A1 and A2.

During acceleration of the probe stylus 39 the articulated probe head applies a torque to the Z column of the CMM. In particular during measurement of certain profiles such as bores, the stylus may oscillate about the A1 axis creating a torque on the Z column.

Typically the Z column of the CMM is made of granite, which has high stiffness. However the bearings 14 which support the Z column and allow it to move in the Z direction are positioned close together. The positioning of these bearings allows some roll of the Z column. Thus when a torque is applied to the Z column by the articulated probe head, this may cause some roll of the column. As the lower torsional stiffness provided by the bearings is the major factor in causing the roll of the Z column, the position in Z of the column has very little effect on the amount of roll.

Referring to Fig 3 the amount of roll $\delta\theta$ of the Z column 12 causes an error δx in the position of the stylus tip 40.

In a first step of the method the roll stiffness of the Z column 12 must be determined. This may be done by applying a torque to the Z column and measuring the angular deflection θ. For example, a pulley system may be used to evenly apply a known torque to the Z column, whilst an angular interferometer or other angle measuring means is used to measure the rotation of the Z column.

The torque applied by the articulated probe head may be determined in several different ways. If the motors of the probe head are direct drive motors the torque may be determined by measuring the current in the motors. Alternatively a torque cell may be placed between the Z column and the articulating probe head to directly measure the torque applied by the articulating probe head to the Z column.

Using this method it is possible to create data relating to a range of torques applied to the Z column and the corresponding angular deflections of the Z column.

Fig 4 illustrates a graph of torque T against Z column angular deflection $\delta\theta$. From Hooks law, $\delta\theta = T/k$ where k is the roll stiffness. Once k is known, all future measurements can be corrected using this equation.

Referring back to Fig 3, the error δx in the position of the stylus tip 40 caused by the roll of the Z column 12 is an angular error. It's magnitude is therefore proportional to the offset R of the stylus tip 40 from the A1 axis of the articulating probe head 10. The offset $R = L\cos\varphi$, where L is the length of the stylus 39 and φ is the angle of the stylus from the horizontal.

The measurement error δx is therefore $\delta\theta L\cos\varphi$, where $\delta\theta$ is the angular error of the Z column calculated from the torque applied to it.

The angular deflection $\delta\theta$ may be calculated from the torque applied as described above or determined using a

look-up table from a mapped articulating probe head.

An alternative method of determining the δx measurement error is to experimentally record it by scanning a calibrated artefact. As before the torque applied to the column by the probe head is measured by using a torque cell or by measuring the current used by the direct drive motors. The difference between the measured dimensions of the artefact and the known dimensions of the artefact are a measure of the $\delta\theta$ error. As before the relationship between the torque applied and the error $\delta\theta$ may be used to determine k the roll stiffness using Hooks law or to create data to use in a look-up table. In a variation of this method a non-calibrated artefact may be scanned first at a slow speed and then at a fast speed. When scanned at a slow speed, the measurement errors due to Z column roll are negligible as the accelerations are very low. The $\delta\theta$ error is the difference between the measurements obtained from these fast and slow speeds.

Using these methods the error δx of the stylus tip caused by the torque applied by the probe head can be determined and therefore this error caused by the roll of the Z column can be corrected. This invention therefore enables mathematical compensation of the measurement error.

This method enables high speed measurements to be taken as the measuring error caused by these high speed measurements can be compensated mathematically. Furthermore as mathematical compensation is possible a non-inertia balanced probe head may be used. Thus reducing cost, complexity and weight of the probe head.

The method is not limited to use with vertical arm coordinate positioning machines. For example, it is also suitable for use with horizontal arm coordinate positioning machines.

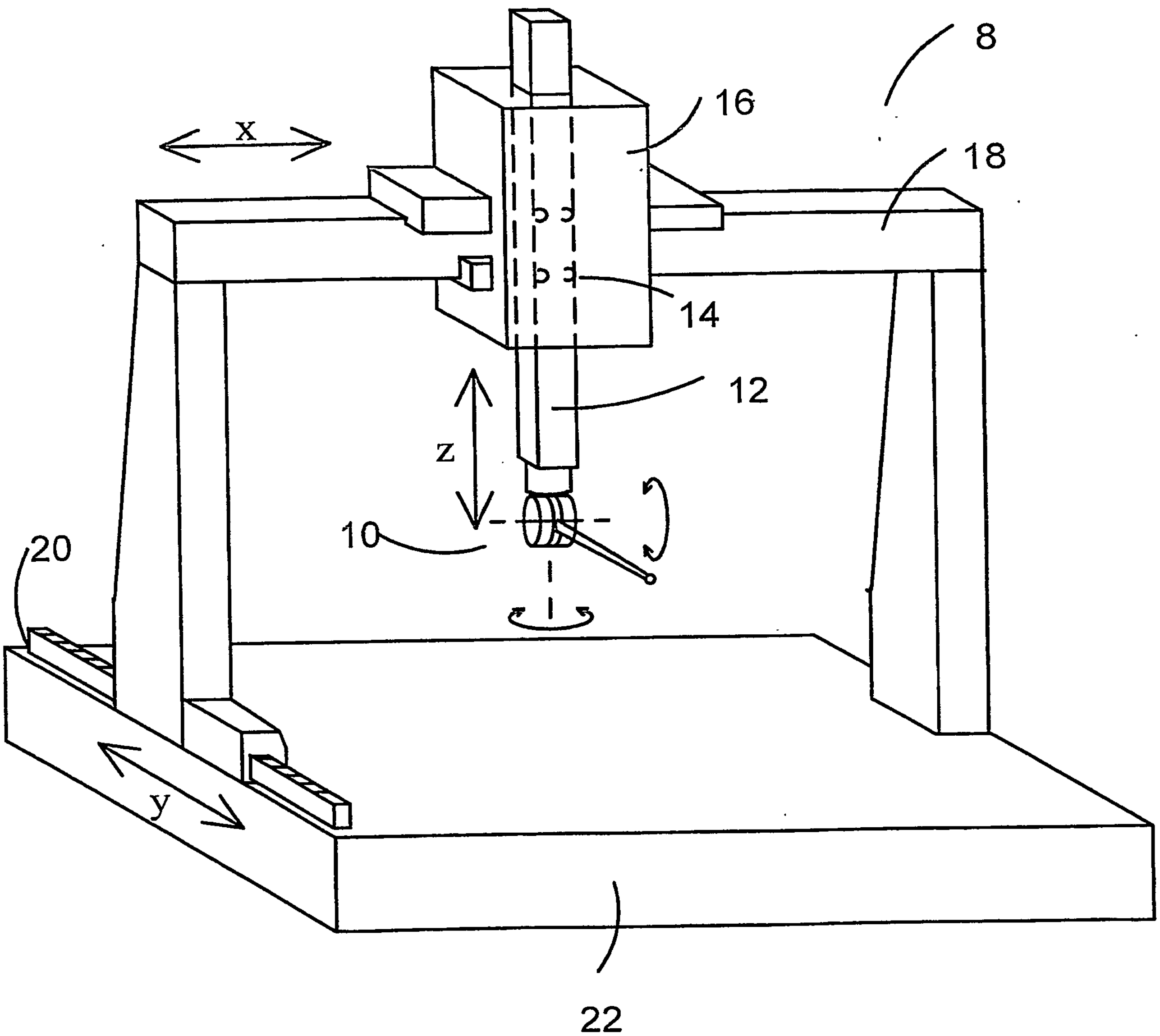

Fig 1

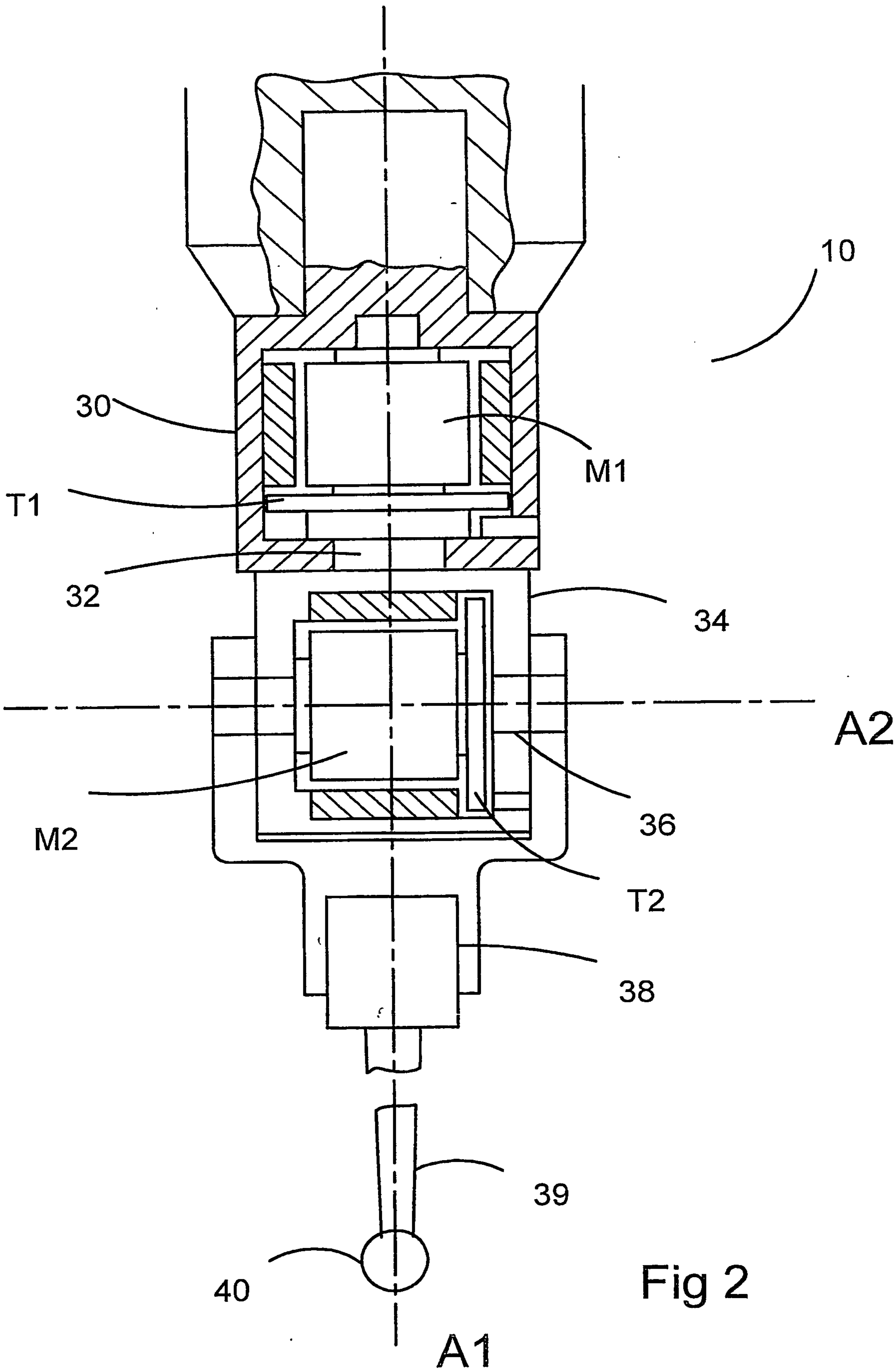

Fig 2

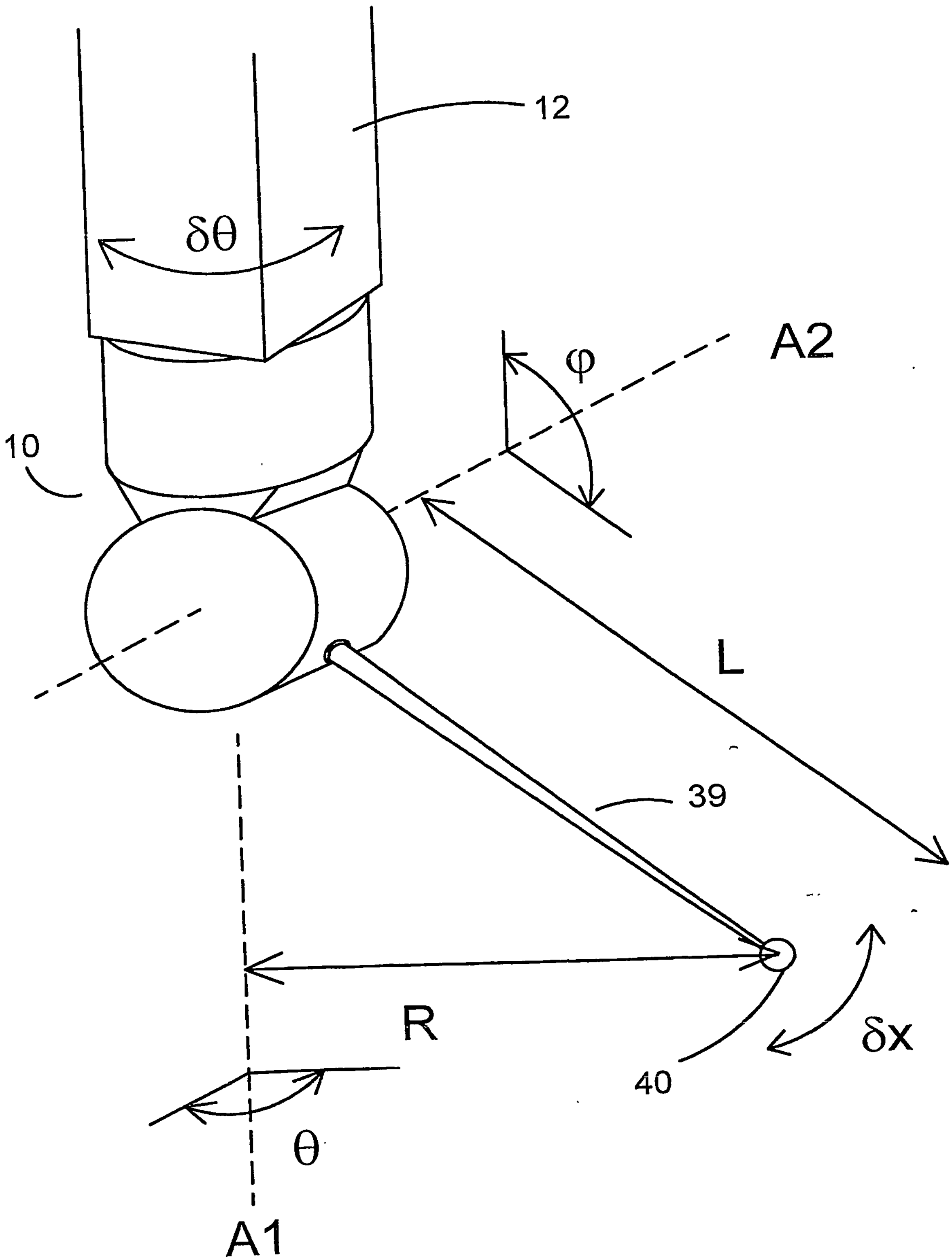

Fig 3

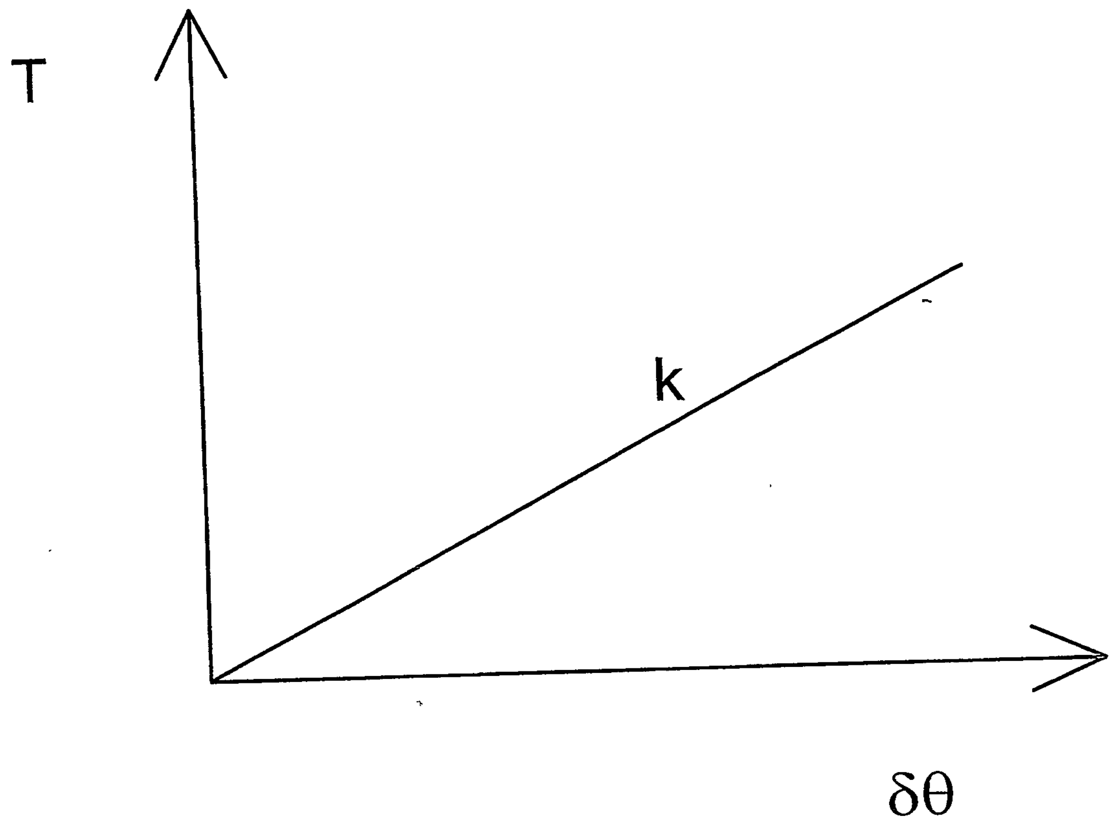

Fig 4